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Final Report on Contract
Nonr 610(03)

WELDED CONTINUOUS FRAMES AND THEIR COMPONENTS

This report is submitted in compliance with contract 610(03). The research project is being continued under a contract with the Bureau of Ships.

July 30, 1963

Fritz Engineering Laboratory
Civil Engineering Department
Institute of Research
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Bethlehem, Pa.

WELDED CONTINUOUS FRAMES AND THEIR COMPONENTS

Final Report on Contract 610(03)

I. INTRODUCTION

This report is submitted to the Office of Naval Research in compliance with Contract Nonr 610(03). It is occasioned by the transfer of sponsorship of this project from the Office of Naval Research to the direct sponsorship of the Bureau of Ships. The topic of this investigation has been the plastic strength of indeterminate steel structures and the study of the plastic behavior of the component parts of such structures. A special portion of the work has been an investigation of the strength of longitudinally stiffened plate panels.

This investigation has been sponsored jointly by the Navy Department and the Welding Research Council. The Navy Department sponsorship was begun under contract 393(03) and was continued under contract 610(03) beginning in September 1956. A final report on the work under contract 393(03) was submitted on December 1, 1956. The work performed under contract 610(03) during the period from September 1956 to December 31, 1962 is summarized in the present report. During this period the Navy Department's contribution provided all of the funds for the stiffened plate panel investigation and 19 percent of the funds for the welded continuous frames investigation.

In the following pages are given a statement of project objectives (Section II), a general survey of work accomplished (Section III), an index of the unpublished reports (Section IV), and an index of papers which have been published (Section V). The reports listed in Sections IV and V may be referred to for any details of particular interest.

II. PROJECT OBJECTIVES

The original objectives, approved at the March 1950, meeting of the Lehigh Project Subcommittee are as follows:

1. To determine the behavior of steel beams, columns and continuous welded connections with emphases on plastic behavior, and to develop theories to predict such behavior.
2. To determine how to proportion various types of welded continuous frames to develop the most balanced resistance in the plastic range so that the greatest possible collapse load will be reached.
3. To determine procedures of analysis that will enable one to calculate the collapse loads of welded continuous frames and to verify the analysis by suitable tests.
4. To determine procedures of analysis that will enable one to calculate the elastic and permanent deformations in welded continuous frames in the range intermediate between the elastic limit and collapse load.
5. To explore limitations in the application of plastic design over and above deformation limitations, namely, fatigue, local buckling, lateral buckling, etc.
6. To develop practical design procedures for the utilization of reserve plastic strength in the design of continuous welded frames.
7. To determine the strength of longitudinally stiffened plate panels (ship bottom plating) subjected to lateral and axial loading.

In brief, then, the program consists of:

1. Column, Beam and Connection Studies (Frame Components)
2. Frame Studies (Integral Behavior)
3. Practical Applications (Methods of analysis and design with due regard to limitations such as fatigue, deflections, local buckling, etc.)

III. SUMMARY OF WORK COMPLETED

3.1 General Survey

During the course of this contract, numerous tests have verified the validity of theories predicting the reserve of plastic strength above first yield of continuous structures. Furthermore, studies of necessary modifications to the simple plastic theory have progressed to the stage where the plastic design procedure could be documented.

Outstanding among the more recent publications which document the plastic design procedure are:

1. The "Commentary on Plastic Design in Steel", ASCE Manual of Engineering Practice No. 41 (1961);
2. The 1963 AISC "Specification for the Design, Fabrication, and Erection of Structural Steel for Buildings"; and
3. "Structural Steel Design" by the Civil Engineering Department staff of Lehigh University (1962).

The first of these publications was prepared under the direction of a Joint Committee of the Welding Research Council and the American Society of Civil Engineers and is based on a series of reports by the research team at Fritz Engineering Laboratory, Lehigh University. The "Commentary" presents the necessary information to the structural engineering profession to justify suggested analysis and design procedures based upon the plastic method. The combined efforts of the Joint Committee and the Fritz Laboratory research team resulted in this widely accepted publication which is rapidly becoming a standard reference in the plastic design field.

The 1963 AISC Specification points the way to greater economy and flexibility in steel construction through the utilization of the plastic strength of continuous steel structures. This Specification relies heavily on the results of plastic design research at Lehigh University and other institutions. For the first time, both plastic design and allowable stress (conventional) design are included in this nationally recognized Specification. Even the allowable stress design provisions incorporate the results of research on the plastic strength of structures.

Publication of the AISC Specification provided the impetus for the notes on structural steel design. These notes include design examples which are based essentially upon the new AISC Specification and are intended to illustrate its provisions. The results of much of the theoretical and experimental research, which are the basis for the many new provisions of the Specification, are included in the notes as background. Plans to distribute these notes to engineering schools and other interested groups throughout the nation are in progress, under the auspices of the American Institute of Steel Construction and Lehigh University.

Since its inception, this project has been conducted on the premise that a complete research endeavor comprizes both the synthesis and distribution of new knowledge. These three publications represent a portion of the educational effort relevant to the Welded Continuous Frames project. Other elements of the educational effort (since 1957) include:

1. Regional conferences of the AISC; 40 sumposiums held at universities throughout the nation.
2. AISC sponsored evening lecture series
3. AISC Specification Announcement Conferences

In addition, members of the project staff participated in more general conferences dealing with plastic design such as:

1. The ASCE-IABSE Conference, New York , 1958
2. ASCE Convention on "Plasticity in Design", Los Angeles, 1959
3. Second Symposium on Naval Structural Mechanics, Brown University, 1960
4. ASCE Convention, Structural Division Sessions, Houston, 1962
5. Seminar on Structural Steel Design, Lehigh University, 1962
6. 8th Summer Scientific Conference on Civil Engineering, Krynica, Poland, 1962

The technical publications listed in Section V of this report serve to broaden and complete the educational effort.

During the course of this contract, significant progress has been made in several areas which include:

1. Stiffened plate panels
2. Corner connections
3. Lateral-torsional buckling of beams
4. Frame stability
5. Columns
6. Multi-story frames

Both theoretical and experimental research has resulted in means for predicting structural behavior in the plastic range for each of these topics. Design recommendations have been developed in many cases.

The research sponsored in part by this contract provided the subject matter for four MS degrees and eight PhD dissertations. Six of the twelve men who received graduate degrees have continued as project staff members.

3.2 Stiffened Plate Panels (Supported by ONR)

Several phases of an experimental investigation of longitudinally stiffened plate panels have been completed. (See the 248 series of Fritz Engineering Laboratory Reports). This study intends to develop procedures for the strength analysis of stiffened panels subjected to the loading conditions encountered in ship structures. Completed phases of the program include:

1. Six tests (T-1 to T-6) to investigate the effect of lateral loading and rotational restraint offered by stiffeners on the strength of stiffened plate panels.
2. Three tests (T-7 to T-9) to investigate the influence of welding residual stresses on the stability of stiffened panels. These tests were conducted without lateral loading. An additional specimen was used to measure residual welding stresses.
3. Determination of material properties of the plates in compression and tension.
4. A theoretical study of the elastic-plastic strength of a simply supported plate subjected to lateral and axial loading. This study was desirable since the strength of the plate affects the strength of the stiffened panel assembly.

A new series of tests is currently in progress to determine the influence of end restraint on the strength of stiffened plate panels. These tests are intended to assess the effects of continuity in ship bottom construction.

The results of the completed phases of this investigation indicate that:

1. The strength of stiffened plate panels with a width to thickness ratio b/t less than 60 is controlled by plate buckling.
2. The effect of lateral pressure on plate buckling, for b/t = 60, is negligible.
3. Welding residual stresses may considerably reduce the panel strength for b/t = 60, but their influence is negligible for b/t = 40.
4. The static yield point of the plate material in compression is from 5 to 8 precent higher than the tensile static yield point.

The test specimens were fabricated from ASTM A7 steel with an average static yield point of 40 ksi.

A simplified non-destructive technique for measuring welding residual stresses in plates has been developed as a by product of this study. (See Fritz Engineering Laboratory Report No. 248.11). This method features comparative speed and economy. It also permits residual stress measurements on the test specimen itself rather than on a companion specimen. Companion specimens do not necessarily exhibit the same distribution of residual stresses because of variations in weld sequence, speed, and other welding variables. The non-destructive technique is not limited to laboratory use any may have future application as a quality control device in welded fabrication.

Another topic in the investigation of the strength of welded built-up members was concerned with the influence of high shear and axial forces on the plastic moment capacity. A theoretical and experimental investigation of this problem has been completed. (See Fritz Engineering Laboratory Report No. 248.1). The results of this study are design equations for the plastic moment reduction due to; shear, thrust, or shear and thrust. These equations are based on the lower bound concept of the plastic theory.

3.3 Rigid Frames (Supported by ONR and WRC)

A reduction in main member sizes and an increase in stiffness are two advantages which are obtained by using haunched connections in continuous frames. In the early stages of plastic design it was thought necessary that haunches should remain elastic at ultimate load. A completed investigation of haunched connections has shown that this requirement is unnecessary. The results of this study are a series of plastic design rules for curved and tapered haunches. (See the 205C series of Fritz Engineering Laboratory reports). The investigation included full size tests of haunched connections. These tests verified that haunches, proportioned using the design rules, will provide adequate strength and rotation capacity.

Considerable progress has been made toward an understanding of the frame stability problem for rigid frames. The results of four series of small scale frame tests were used to verify a two parameter (axial load and slenderness ratio) frame stability design guide for the columns of a plastically designed frame.

A numerical integration method was devised for the analysis of portal frames in the elastic and plastic ranges of loading. This method, which takes rational account of bending moments induced by axial loads, was then used to investigate both the symmetric and the sway modes of instability for a number of single story frames. This study produced an improved design guide for frame stability which includes the influence of beam stiffness. Another recently completed item is the frame stability literature survey which includes a valuable tabulation of available solutions to many frame stability problems.

The lateral bracing required to sustain adequate hinge rotation in plastically designed beams has been the subject of extensive study. This study aims to determine the optimum required spacing and stiffness of the lateral bracing which will sustain adequate post-buckling strength and rotation capacity for wide-flange beams. Completed phases of this investigation have resulted in design provisions for the spacing and stiffness of purlins which function as bracing. Under current investigation are the effects of: moment gradient, number of critical spans, plastic hinges in the purlins and moment redistribution.

Successful efforts have been made to determine the ultimate strength of beam-columns, considered as isolated members or as restrained columns in a rigid frame. The ability to predict the behavior of beam-columns in the elastic-plastic range of loading has eliminated a troublesome gap in the plastic design method.

The moment-rotation behavior and ultimate strength of isolated beam-columns have been investigated both analytically and experimentally with good agreement between theory and tests. The result of this work is a set of ultimate strength interaction curves and tables for beam-columns with constant end-moment ratios. These interaction curves form the basis for the beam-column provisions of the 1963 AISC Specification.

A generally valid method for predicting the deflected shape of beam-columns has been developed from the study of column deflection curves. The column deflection curve concept takes rational account of many factors which influence the behavior of beam-columns. Topics under current investigation, using the column deflection curve concept include:

1. Lateral-torsional buckling of beam-columns under a moment gradient
2. The beneficial influence of restraining beams on the ultimate load capacity of beam and column subassemblages in braced multi-story frames, and
3. The weakening effect of sway in unbraced multi-story frames

Future work on the topics resulting from the column deflection curve study promise to permit a more rational and economical design of compression members in ship and building structures.

One of the important research projects in plastic design is concerned with multi-story frames. The investigation of braced multi-story frames has produced a plastic design procedure for the beams, columns, and bracing which fully utilizes the column restraint offered by the beams and the plastic strength of the rigid frame. Comparative design studies indicate that this plastic design procedure can result in significant economy as compared with conventional design methods for multi-story frames. An experimental program to verify the predictions of this procedure is in progress.

A study of unbraced multi-story frames has been initiated. An unbraced frame analysis is complicated by the relative horizontal deflection which occurs between the floors of the frame due to horizontal loads and which significantly influences the column moments.

Recently, a rational analysis to determine the load-deflection response of unbraced multi-story frames, including sway effects, has been outlined. The method is exact in the sense that all necessary equilibrium (in the deflected state), plastic moment, and compatibility conditions are satisfied. It is anticipated that this method will be useful for checking and improving the assumptions made in approximate analyses of multi-story frames, for making rational ultimate strength predictions, and for formulating design guides and their limitations.

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